Correlated Production of the Λ_c

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Abstract

When we model the way that particles are produced from e^+e^- interactions it is a common assumption that the mode through which fragmentation leads to particle production in one hemisphere occurs largely independently of particle production in the opposite hemisphere. In this paper we will present our measurements of the correlated production of the Λ_c baryon. Through our studies of the Λ_c baryon, we have found evidence that Λ_c's have a greater probability of being produced opposite their antiparticle as opposed to opposite an anti-charmed meson. This effect was measured to be 3.47 ± 0.98 times as likely in finding a Λ_c^+ particle opposite a Λ_c^- particle rather than a $\overline{D^0}$.

Introduction

The purpose of this analysis is to test the assumption that particles fragment independently of one another. This is a question which tests the very fundamentals of our understanding of the mechanism by which particles form and interact. The difficulty in testing this assumption lies in properly isolating a specific hadron-antihadron pair that may experience correlated production, and which may also be measurable. The Λ_c baryon provides us with just such an opportunity. If we select high momenta Λ_c's, we can remove any Λ_c's that may have been produced as a result of $\mathrm{b\bar{b}}$ pair production and we can assume $e^+e^- \rightarrow \mathrm{c\bar{c}}$ events. Further, the Λ_c has enough statistics for $\Lambda_c\overline{\Lambda_c}$ production to be measured accurately.

Theory

If we assume that when primary particles undergo fragmentation, their fragmentation occurs independently of one another, then we would assume that the number of times that we find a Λ_c^+ baryon opposite a Λ_c^- antibaryon in an event, scaled per total number of Λ_c events ($\frac{\Lambda_c^+|\Lambda_c^-}{\Lambda_c^-}$), should be equal to the number of times that we find a ${\Lambda_c}^+$ baryon opposite any other charmed hadron ($\frac{\Lambda_c^+|\overline{H_c}}{\overline{H_c}}$), scaled to the total number of events containing this charmed hadron. Rates in this form will be referred to as production rates.

Schematically, we are comparing the following event topologies:

$$\Lambda_c^- \hookleftarrow \quad \overset{\overline{c} \quad c}{} \quad \hookrightarrow \Lambda_c^+$$

$$vs$$

$$\overline{H_c} \hookleftarrow \quad \overset{\overline{c} \quad c}{} \quad \hookrightarrow \Lambda_c^+$$

In this analysis, we will compare the rate of $\Lambda_c^+\Lambda_c^-$ production versus the rate of $\Lambda_c^+\overline{D^0}$ and $\Lambda_c^+D^+$ productions. We choose D^0's and D^+'s through the well defined decay modes Kπ and K$\pi\pi$, respectively. The Λ_c's are reconstructed via three decay possibilities, pKπ, pK_s^0, and Λ + X, as shown:

$$
\begin{array}{rrccll}
 & & \bar{c} & c & & \\
 & \Lambda_c^- \hookleftarrow & & & \hookrightarrow \Lambda_c^+ & \\
\bar{p}K^+\pi^- \hookleftarrow & & & & & \hookrightarrow pK^-\pi^+ \\
\bar{p}K_s^0 \hookleftarrow & & & & & \\
\overline{\Lambda} \hookleftarrow & & & & & \\
\bar{p}\pi^+ \hookleftarrow & & & & &
\end{array}
$$

$$
\begin{array}{rrccll}
 & & \bar{c} & c & & \\
 & \overline{D^0} \hookleftarrow & & & \hookrightarrow \Lambda_c^+ & \\
K^+\pi^- \hookleftarrow & & & & & \hookrightarrow pK^-\pi^+ \\
 & D^- \hookleftarrow & & & & \hookrightarrow p\overline{K_S^0} \\
K^+\pi^-\pi^- \hookleftarrow & & & & & \hookrightarrow \Lambda
\end{array}
$$

All three of these modes are well defined, and provide us with different advantages. The mode $\Lambda_c \to$ pKπ generates a large sample of events, while the mode $\Lambda_c \to$ pK_S^0 has a good ratio of signal to noise. The Λ's are utilized under the assumption that they are produced from a Λ_c. This assumption was measured by Bull and Holliday to be 95% pure under the condition that the momentum of the $\Lambda > 1$ GeV/c and that a charmed hadron is reconstructed in the event. Since we assume that these rates should all be equal, we will measure this process in terms of the quotient of these rates, which is assumed to be equal to unity under the assumption of independent fragmentation.

$$\frac{\Lambda_c^+|\Lambda_c^-}{\Lambda_c^+} \div \frac{\Lambda_c^+|\overline{D^0}}{\overline{D^0}} = 1$$

and,

$$\frac{\Lambda_c^+|\Lambda_c^-}{\Lambda_c^+} \div \frac{\Lambda_c^+|D^-}{D^-} = 1\ .$$

These ratios of the production rates will be referred to as production ratios.

Analysis Method

This analysis is based on selecting particles that have been generated from c$\bar{\text{c}}$ events and determining their respective production rates. In particular, it is necessary to determine the number of events that produce each of two particles, called "double tags".

Double Tag Method

We define the number of single tags events to be the number of reconstructed events containing one particle decaying in a given decay mode. The number of double tags is defined as the number of reconstructed events containing each of two particles which have

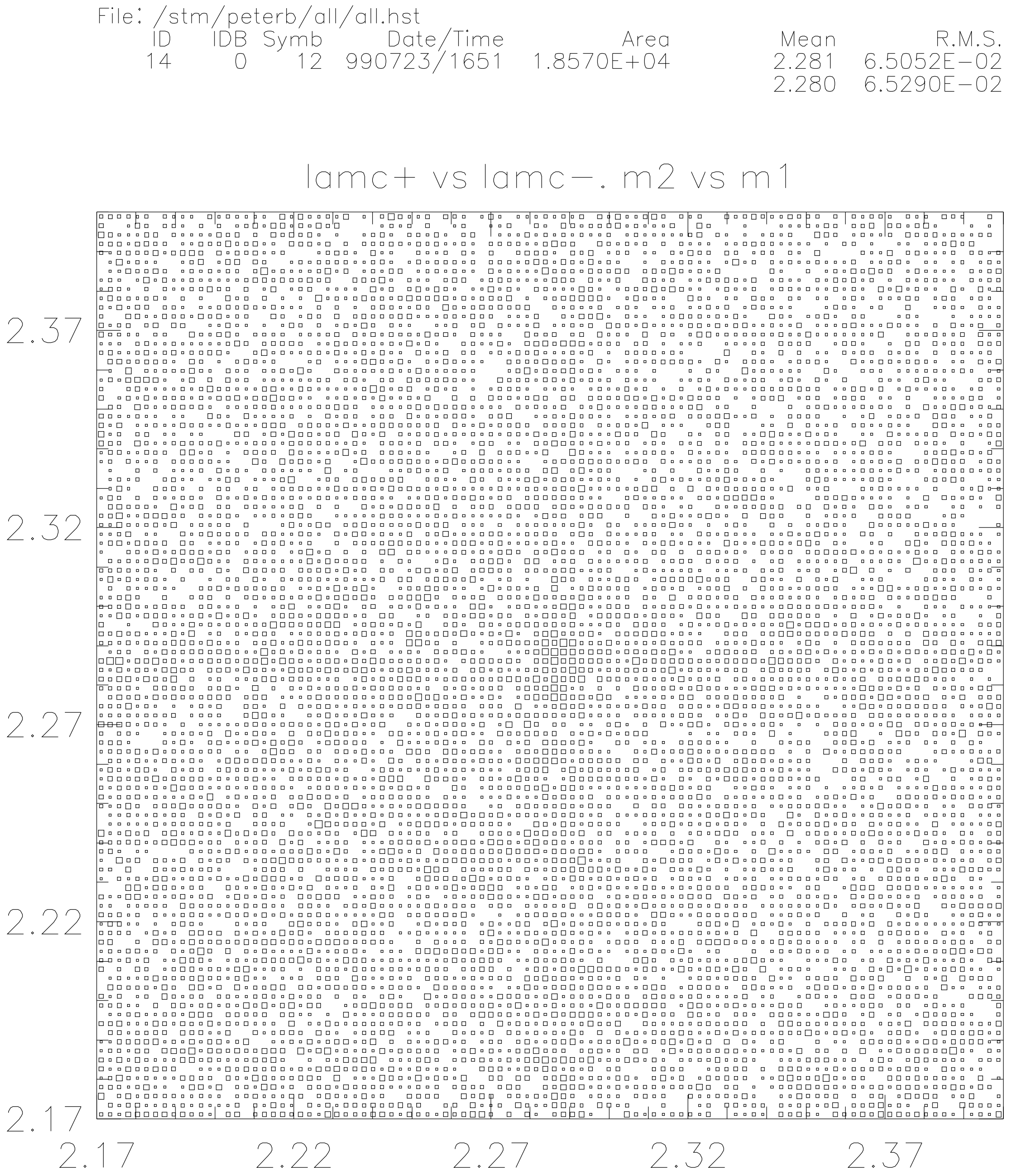

FIGURE 1. This is the double tag plot of $(\Lambda_c^+|\Lambda_c^-)$ for data. The signal can be seen at the intersection of the mass value of the Λ_c, 2.2867 GeV/c^2.

decayed via their chosen decay modes. The invariant masses of the two particles which we have selected to double tag with this method are plotted versus one another, as illustrated in Figure 1. This two-dimensional mass versus mass plot will display a peak region located at the intersection of the mean mass value of the two particles.

However, while the peak region may often appear to be quite apparent for a given double tag plot, the dynamics of the events that contribute as background may not appear to be as obvious. We must take into consideration the fact that we may be correctly reconstructing one of the particles comprising the double tag and not the other. Events such as these will show a correlation to the mass value of one of the particles and not the other. Such events will appear as a strip of events along the mass value of one of the particles. Assuming that events of this type will occur for each particle, there will be two strips of these events for each double tag plot. These events will be contributing to our background as well as any normal background of random, uncorrelated particles (such as those that appear in a one dimensional single tag plot of the invariant mass).

We therefore have a background that consists of both random, mis-reconstructed particle events, and correctly reconstructed particles that do not come from the same events. This second form of background will contribute differently to the background in the double tag peak region than in the rest of the background. Here, the overlap of the two uncorrelated strips of correctly reconstructed particles will incorrectly enhance the signal region and must be accounted for.

The solution, therefore, is to measure the amount of uncorrelated particles that appear outside of the signal and conduct a sideband subtraction with these particles by scaling them and subtracting them from our signal region.

The following describes the method by which the true number of double tag signal events is determined. First, the signal and background regions for one of the particles in the double tag are cut out in slices. The signal and background are then projected onto the mass axis of the other particle, and a gaussian likelihood fit is applied to each projection, with the mean and sigma having been fixed to the values obtained from the single tag fit of the same particle decaying via the same decay mode. With the exception of the fits to the mass of the Λ^0, the random background for all of these projections is assumed to be linear and is fitted with a first order Chebyshev polynomial. In order to take into account the proximity of the Λ^0 mass to the $p\pi$ threshold, the background region for the Λ^0 is fitted with a third order Chebyshev. A similar fit is applied to the signal region to determine the total number of signal double tag events. The signal number of uncorrelated data obtained from the background fit is then scaled and subtracted from the number of signal events to get the number of double tag events. The scaled error of the number of background events is then added quadratically to the error in the number of signal events.

However, each of these double tag plots consist of the mass values of two particles plotted verses one another. The true number of double tags is taken as the average of the value obtained from projections onto each mass axis. The variation of this average value from the value of either projection is included as a systematic error. This is the method by which we account for the total background when we extract the true value of our double tag signal.

Calculations

In this paper we will present our measurement in two different manners. The first manner of presenting our measurement is in terms of production ratios, which were defined as the ratios of two production rates. This is our preferred convention for presenting this measurement. The second manner of presenting our measurement is through calculating the expected values for the measurement and comparing them to the measured values. This latter method includes several estimates and approximations; as such, it is much more prone to systematic error and is not the preferred way to quote our results.

Production Ratios

The calculations of the production ratios are very simple and straight forward. The production ratios are just a comparison of the calculated production rates. The production rates are the rate of finding a double tag for every single tag that we find. To put it another way, the production rate is a measurement of the percentage of the time that we find one particle in an event opposite the other one.

TABLE 1. Double Tags

	Data	Monte Carlo
$\Lambda_c \to \mathrm{p}K\pi$		
$\Lambda_c^+\vert\Lambda_c^-$	93.6 ± 21.9	-27.1 ± 14.0
$\Lambda_c^+\vert\overline{D^0}$	434.1 ± 44.1	376.8 ± 35.6
$\Lambda_c^+\vert D^-$	367.2 ± 64.7	215.0 ± 50.2
$\Lambda_c^+\vert\overline{\Lambda}$	1042.4 ± 59.7	245.8 ± 38.4
$\Lambda_c \to \mathrm{p}\overline{K_S^0}$		
$\Lambda_c^+\vert\Lambda_c^-$	28.80 ± 9.02	9.34 ± 6.19
$\Lambda_c^+\vert\overline{D^0}$	73.3 ± 12.8	65.7 ± 11.2
$\Lambda_c^+\vert D^-$	70.4 ± 17.0	29.5 ± 12.5
$\Lambda_c^+\vert\overline{\Lambda}$	130.8 ± 15.8	10.17 ± 9.03
$\Lambda\vert\overline{D^0}$	2247.4 ± 74.7	1840.9 ± 64.8
$\Lambda\vert D^-$	2031 ± 102	1513.9 ± 85.4

TABLE 2. Single Tags

	Data	Monte Carlo
$\Lambda_c \to \mathrm{p}K\pi$	40362 ± 698	24715 ± 539
$\Lambda_c \to \mathrm{p}\overline{K_S^0}$	6750 ± 152	3613 ± 115
$\Lambda \to \mathrm{p}\pi$	670200 ± 1000	465680 ± 812
$D^0 \to K\pi$	325200 ± 1040	238939 ± 838
$D^\pm \to K\pi\pi$	256730 ± 1450	159630 ± 1180

To obtain the rates we take the true number of double tags (Table 1), as calculated via our method, and divide them by the number of single tags (Table 2). These rates are listed in Table 3. Finally, the production ratios are a comparison of these rates by their quotient. These ratios are listed in Table 4.

TABLE 3. Production Rates

$\frac{\textit{Double tags}}{\textit{Single tags}}$	Data Fraction	Monte Carlo Fraction
$\Lambda_c \rightarrow$ p$K\pi$		
$\frac{\Lambda_c^+ \vert \Lambda_c^-}{\Lambda_c^-}$	(4.64 ± 1.09) x 10^{-3}	(-2.20 ± 1.14) x 10^{-3}
$\frac{\Lambda_c^+ \vert \overline{D^0}}{\overline{D^0}}$	(1.335 ± 0.136) x 10^{-3}	(1.577 ± 0.149) x 10^{-3}
$\frac{\Lambda_c^+ \vert D^-}{D^-}$	(1.430 ± 0.252) x 10^{-3}	(1.347 ± 0.314) x 10^{-3}
$\frac{\Lambda \vert \Lambda_c^-}{\Lambda}$	(25.83 ± 1.55) x 10^{-3}	(9.95 ± 1.57) x 10^{-3}
$\frac{\Lambda \vert \overline{D^0}}{\overline{D^0}}$	(6.911 ± 0.231) x 10^{-3}	(7.704 ± 0.272) x 10^{-3}
$\frac{\Lambda \vert D^-}{D^0}$	(7.913 ± 0.398) x 10^{-3}	(9.484 ± 0.539) x 10^{-3}
$\Lambda_c \rightarrow$ p$\overline{K_S^0}$		
$\frac{\Lambda_c^+ \vert \Lambda_c^-}{\Lambda_c^-}$	(0.714 ± 0.224) x 10^{-3}	(0.378 ± 0.251) x 10^{-3}
$\frac{\Lambda_c^+ \vert \overline{D^0}}{\overline{D^0}}$	(0.2255 ± 0.0393) x 10^{-3}	(0.2748 ± 0.0469) x 10^{-3}
$\frac{\Lambda_c^+ \vert D^-}{D^-}$	(0.2741 ± 0.0660) x 10^{-3}	(0.1849 ± 0.0781) x 10^{-3}
$\frac{\Lambda \vert \Lambda_c^-}{\Lambda}$	(19.38 ± 2.38) x 10^{-3}	(2.82 ± 2.50) x 10^{-3}

The motivation behind making these calculations in this manner is that these production ratios represent the frequency with which we find the Λ_c^+ opposite the Λ_c^- in an event compared to the number of times that we find a Λ_c^+ opposite a $\overline{D^0}$ or a D^-. Further, by making the measurement in this manner, we take advantage of the fact that the ratio is internally consistent and relies upon no other measurement or estimate for any calculation.

Expected Values

The second form of calculations compares the number of $\Lambda_c^+|\Lambda_c^-$ double tags that we measure with the expected values. The following equations describe the expected number of single tags and double tags, respectively:

$$\#(\Lambda_c)_{SingleTags} = 2 \times \#(c\overline{c}) \times f_{(c\rightarrow\Lambda_c)} \times \mathcal{B}(\Lambda_c \rightarrow pK\pi) \times \epsilon_{pK\pi} \qquad (1)$$

and,

$$\#(\Lambda_c^+|\Lambda_c^-)_{DoubleTags} = f'_{(c\rightarrow\Lambda_c)} \times \mathcal{B}(\Lambda_c \rightarrow pK\pi) \times \epsilon'_{pK\pi} \times \#(\Lambda_c)_{SingleTags} \qquad (2)$$

In Equation (1), the factor of 2 is included to account for both charge conjugates. In Equation (2), the term $f'_{(c\rightarrow\Lambda_c)}$ indicates that the fraction of times that a charm quark produces a Λ_c may be different if the event already contains a $\overline{\Lambda_c}$ produced from the corresponding anticharm quark. The term $\epsilon'_{pK\pi}$ indicates that the efficiency for reconstructing a Λ_c may be higher for events in which a $\overline{\Lambda_c}$ has already been reconstructed due to geometrical considerations of the detector.

TABLE 4. Production Ratios

	Data	Data	Monte Carlo	Monte Carlo
	p$K\pi$	p$\overline{K^0_S}$	p$K\pi$	p$\overline{K^0_S}$
$\frac{\Lambda_c^+\|\Lambda_c^-}{\Lambda_c^-} \div \frac{\Lambda_c^+\|\overline{D^0}}{\overline{D^0}}$	**(3.473 ± 0.888)**	**(3.16 ± 1.14)**	**(-1.393 ± 0.732)**	**(1.374 ± 0.941)**
$\frac{\Lambda_c^+\|\Lambda_c^-}{\Lambda_c^-} \div \frac{\Lambda_c^+\|D^-}{D^-}$	**(3.242 ± 0.951)**	**(2.60 ± 1.03)**	**(-1.631 ± 0.925)**	**(2.04 ± 1.61)**
$\frac{\Lambda\|\Lambda_c^-}{\Lambda} \div \frac{\Lambda\|\overline{D^0}}{\overline{D^0}}$	**(3.737 ± 0.256)**	**(2.804 ± 0.357)**	**(1.291 ± 0.209)**	**(0.365 ± 0.325)**
$\frac{\Lambda\|\Lambda_c^-}{\Lambda} \div \frac{\Lambda\|D^-}{D^-}$	**(3.264 ± 0.255)**	**(2.449 ± 0.326)**	**(1.049 ± 0.176)**	**(0.297 ± 0.264)**

Dividing equation (2) by equation (1) and multiplying each side by $\#(\Lambda_c)_{SingleTags}$ we arrive at the following equation for the number of double tags:

$$\#(\Lambda_c^+|\Lambda_c^-)_{DoubleTags} = \frac{(\#(\Lambda_c)_{SingleTags})^2 \times f'_{(c\to\Lambda_c)} \times \epsilon'_{pK\pi}}{2 \times \#(c\overline{c}) \times f_{(c\to\Lambda_c)} \times \epsilon_{pK\pi}} \tag{3}$$

It is the difference between $f_{(c\to\Lambda_c)}$ and $f'_{(c\to\Lambda_c)}$ which we are essentially trying to measure, as it represents a difference in the production of the Λ_c when a $\overline{\Lambda_c}$ is present. The problem arrives in the fact that the difference between $\epsilon_{pK\pi}$ and $\epsilon'_{pK\pi}$ is not well known. This difference represents the geometrical dependence of our ability to reconstruct each of these particles, and the idea that reconstruction of one of the particles is likely to result in an enhanced reconstruction of the other particle.

The term $\frac{\epsilon'_{pK\pi}}{\epsilon_{pK\pi}}$ is then rewritten as the term $\epsilon_{geometry}$, and $\frac{f'_{(c\to\Lambda_c)}}{f_{(c\to\Lambda_c)}}$ is rewritten as $f_{correlated}$. The latter term is predicted to equal unity under the assumption of independent fragmentation, which we assume when calculating the expected values. The measured values of $f_{correlated}$ are measured by dividing the true number of double tag events by the expected value.

We can make a rough estimate of these values using the following method. First, we calculate the total number of c$\bar{c}$ events. We take the total number of events, we use the assumption that 75% of these events will be hadronic, and that $\frac{4}{10}$ of these events will be c$\bar{c}$ events. We then assume that $f_{correlated}$ is equal to unity and then use equation (3) to calculate $\epsilon_{geometry}$. We use this equation to calculate the total number of $D^0|\overline{D^0}$ and $D^+|D^-$ double tags we would expect to find. We then compare this value with the measured values of these double tags to estimate $\epsilon_{geometry}$. We make the same calculation for the expected number of $\Lambda_c^+|\Lambda_c^-$ double tags. Finally, we multiply the expected value for the number of $\Lambda_c^+|\Lambda_c^-$ double tags by the average value of $\epsilon_{geometry}$ obtained from the D^0 and D^+ estimates to arrive at a corrected expectation for the number of $\Lambda_c^+|\Lambda_c^-$ double tags. This corrected expectation is then compared to the measured number of $\Lambda_c^+|\Lambda_c^-$ double tags to obtain an estimate of $f_{correlated}$. These results are listed in Tables 5 and 6.

Results

The results of our measurement are contained in Tables 4 and 6. Tables 1 and 2 contain the measured values for the number of double tags and single tags. Table 3 contains the Production Rates of double tags divided by single tags. All values are given for both Data

TABLE 5. Expected Values

	Expected	Measured	$\epsilon_{geometry}$
$D^0\|\overline{D^0}$	2191	1964.7 ± 61.1	0.897 ± 0.028
$D^+\|D^-$	1366	1244 ± 117	0.991 ± 0.085
$\Lambda_c^+\|\Lambda_c^-$	33.76		
			0.904 ± 0.057

TABLE 6. Expected $\Lambda_c^+|\Lambda_c^-$ Values

	Expected	$\epsilon_{geometry}$	Corrected	Measured	$f_{correlated}$
$\Lambda_c^+\|\Lambda_c^-$	33.76	0.904 ± 0.057	30.51 ± 1.91	93.6 ± 21.9	3.067 ± 0.717

and Monte Carlo to three significant figures. In Table 4, the production ratios are listed by the mode of Λ_c decay, either p$K\pi$ or pK_S^0. The ratios calculated using the Λ's assume the presence of the Λ_c which has decayed into a Λ.

The full CLEO II (recompress) and CLEO II.V datasets were used, comprising a total of 80.4 million events. The Monte Carlo used in this analysis was composed of a 33.4 million event sample of CLEO II (recompress) and CLEO II.V Monte Carlo.

Conclusions

The measured values of the production ratios imply that the Λ_c is more likely to be produced opposite a $\overline{\Lambda_c}$ than opposite a D^0 or a $D^{\pm}$ by roughly a factor of three. Further, this effect was also seen by comparison of the measured number of $\Lambda_c^+|\Lambda_c^-$'s to the expected value. This effect is not observed in the Monte Carlo. These results indicate strong evidence in support of the correlated production of the Λ_c.

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